FDOT TRANSPORTATION SYMPOSIUM 2019

FRP-RC Design - Part 3b

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Design of concrete structures internally reinforced with FRP bars

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Course Description

Fiber-reinforced polymer (FRP) materials have emerged as an alternative for producing reinforcing bars for concrete structures. Due to other differences in the physical and mechanical behavior of FRP materials versus steel, unique guidance on the engineering and construction of concrete structures reinforced with FRP bars is necessary.

Learning Objectives

- Understand the mechanical properties of FRP bars
- Describe the behavior of FRP bars
- Describe the design assumptions
- Describe the flexural/shear/compression design procedures of concrete members internally reinforced with FRP bars
- Describe the use of internal FRP bars for serviceability & durability design including long-term deflection
- Review the procedure for determining the development and splice length of FRP bars.

Content of the Course

FRP-RC Design - Part 1, (50 min.)

This session will introduce concepts for reinforced concrete design with FRP rebar. Topics will address:

- Recent developments and applications
- Different bar and fiber types;
- Design and construction resources;
- Standards and policies;

FRP-RC Design - Part 2, (50 min.)

This session will introduce Basalt FRP rebar that is being standardized under FHWA funded project ***STIC-0004-00A*** with extended FDOT research under BE694, and provide training on the flexural design of beams, slabs, and columns for:

- Design Assumptions and Material Properties
- Ultimate capacity and rebar development length under strength limit states;
- Crack width, sustained load resistance, and deflection under service limit state;

Content of the Seminar

BFRP-RC Design - Part 3, (50 min.)

This session continues with Basalt FRP rebar from Part II, covering shear and axial design of columns at the strength limit states for:

- Ultimate capacity – Flexural behavior (Session 3a);
- Shear resistance of beams and slabs (Session 3b);
- Fatigue resistance under the Fatigue limit state
- Axial Resistance of columns;
- Combined axial and flexure loading.

FRP-RC Design - Part IV *(Not included at FTS - for future training)*:

This session continues with FRP rebar from Part III, covering detailing and plans preparation:

- Minimum Shrinkage and Temperature Reinforcing
- Bar Bends and Splicing
- Reinforcing Bar Lists
- General Notes & Specifications

Session 3b: *Shear Behavior*

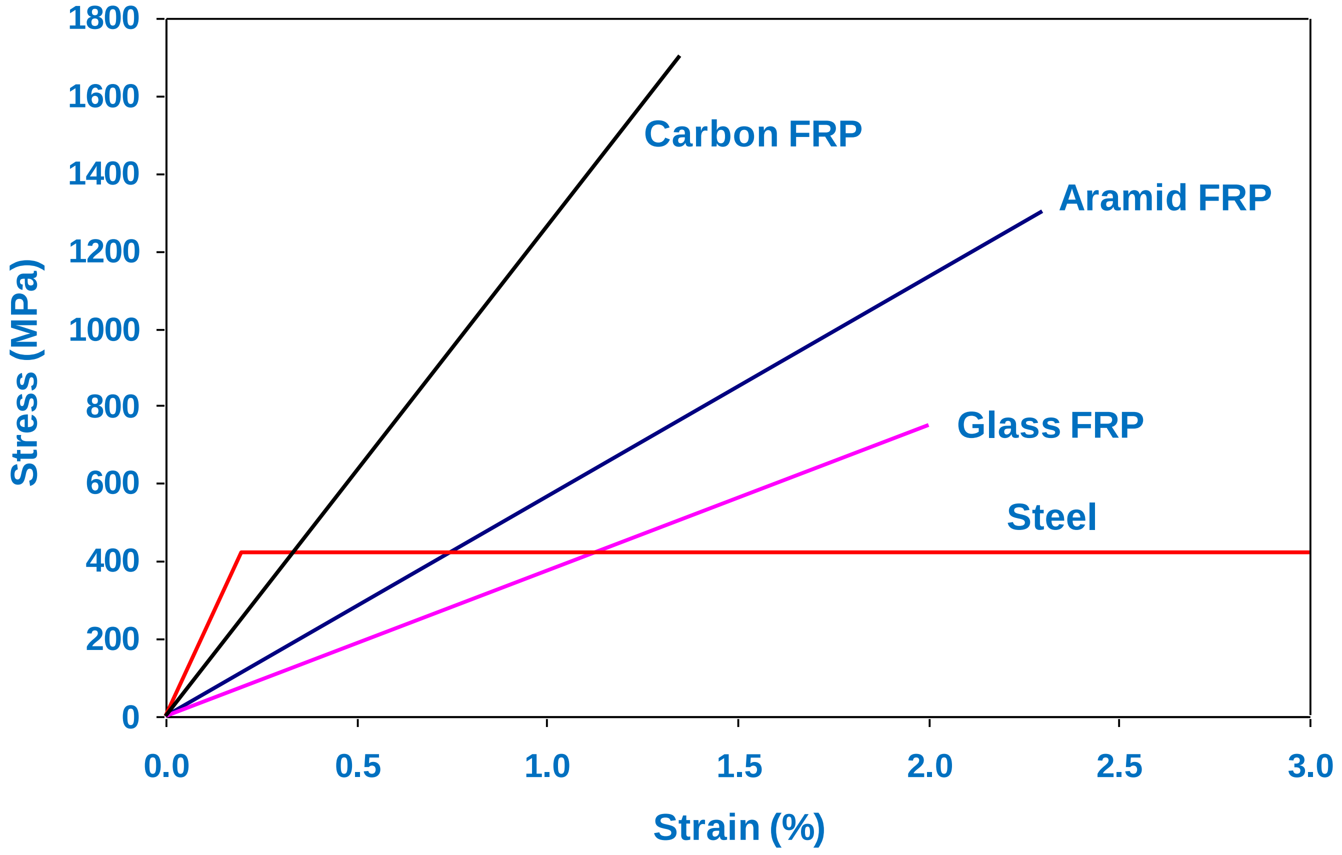
Session 4: (1:30 pm - 2:30 pm)

Shear behaviour

- - Design philosophy
- - Shear strength
- - Design examples

Session 3b: *Shear Behavior*

Stress-Strain Relationships for FRP Bars



Session 3b: *Shear Behavior*

Shear Strength of FRP Reinforced Members

- FRP has a relatively low modulus of elasticity
- FRP has a high tensile strength and no yielding point
- Tensile strength of a bent portion of an FRP bar is significantly lower than a straight portion
- FRP has low dowel resistance

Session 3b: *Shear Behavior*

Shear Strength of FRP Reinforced Members

- Concrete reinforced with FRP has a lower shear strength than concrete with steel reinforcement

- Increased crack width $\longrightarrow$ Less aggregate interlocking
- Small compressive zone depth $\longrightarrow$ Less concrete resistance in the zone compressive

Session 3b: *Shear Behavior*

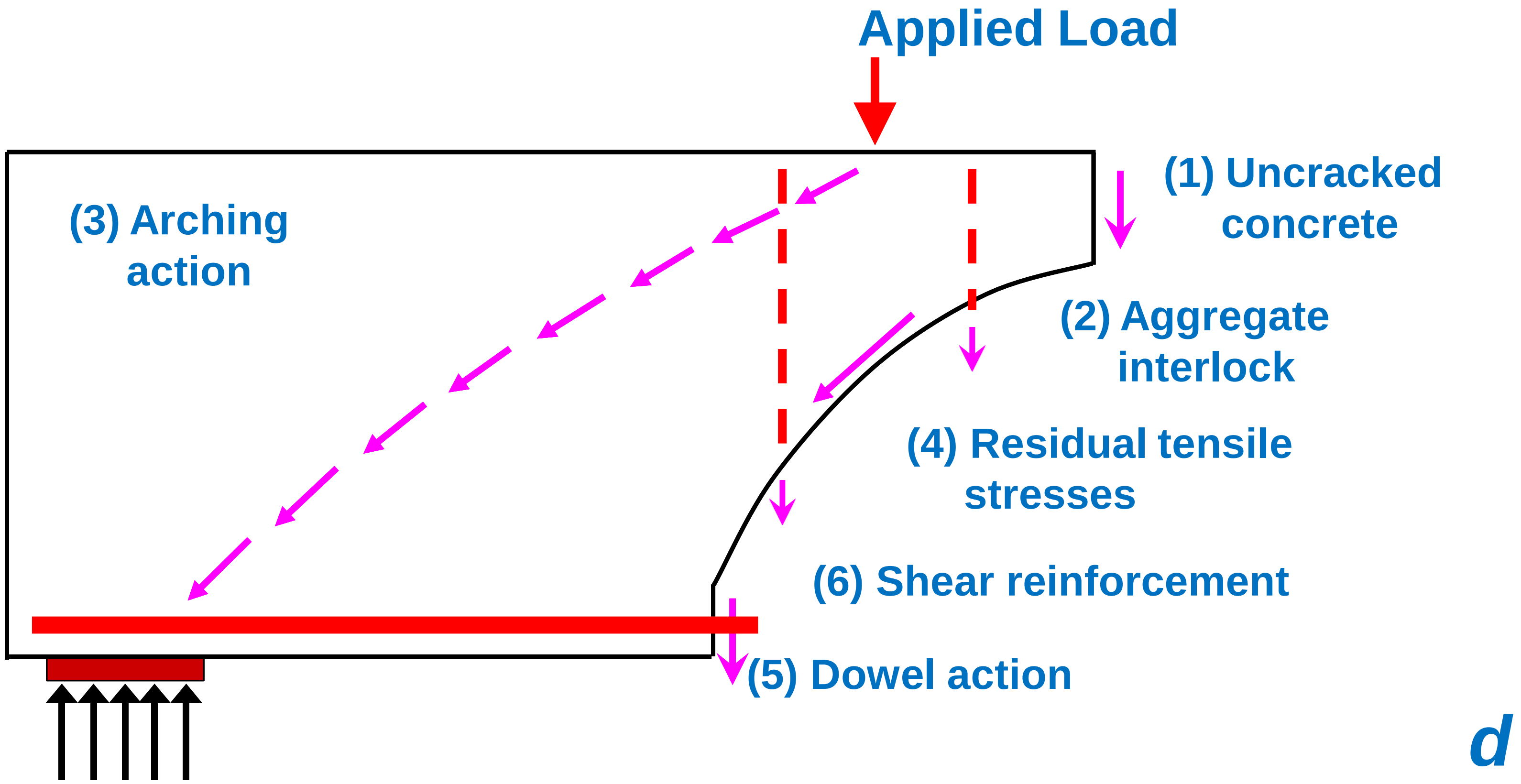
Most of the design codes and design guidelines recommend the following simplified approach for shear design:

$$V_n = V_{cf} + V_{sf} + V_p$$

where

V_n = nominal shear strength
V_{cf} = concrete contribution to shear strength
V_{sf} = shear reinforcement contribution to shear strength
V_p = prestressing resisting component

Session 3b: *Shear Behavior*



Session 3b: *Shear Behavior*

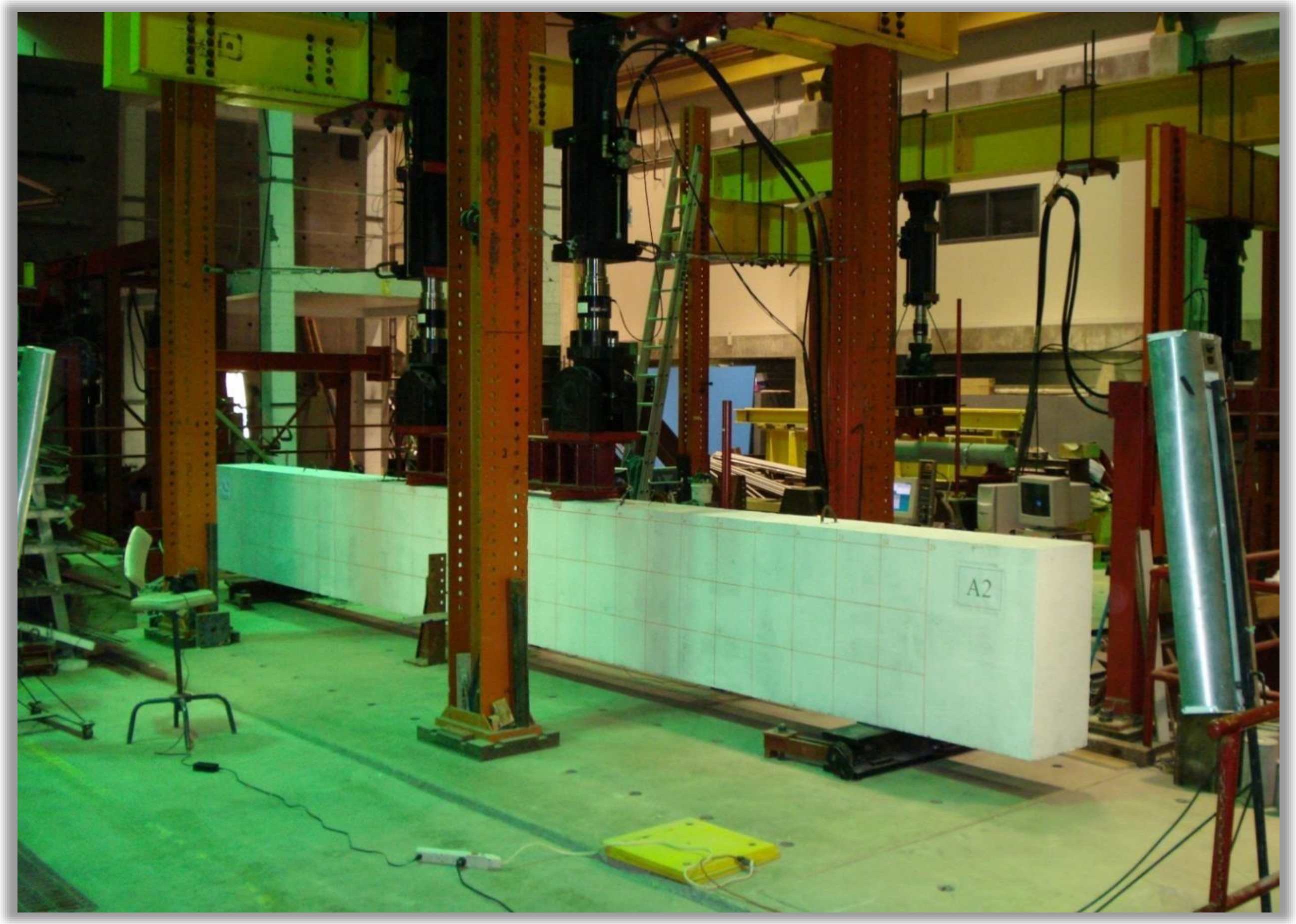
Shear Behaviour of FRP RC Beams

Beam CN-3

Beam GN-3

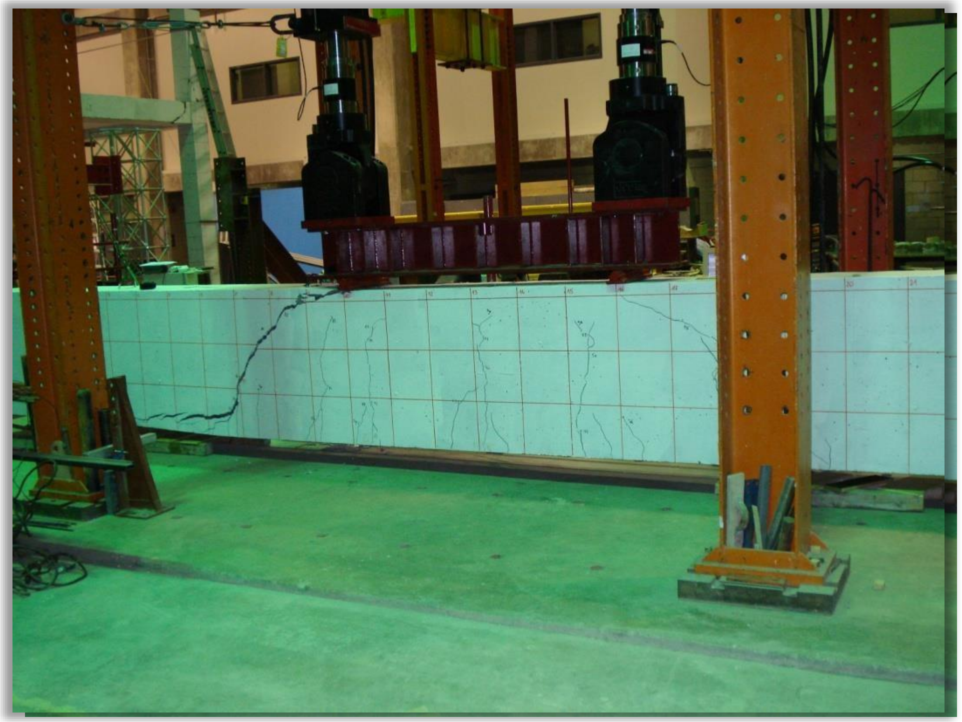
Diagonal tension failure mode

Session 3b: *Shear Behavior*

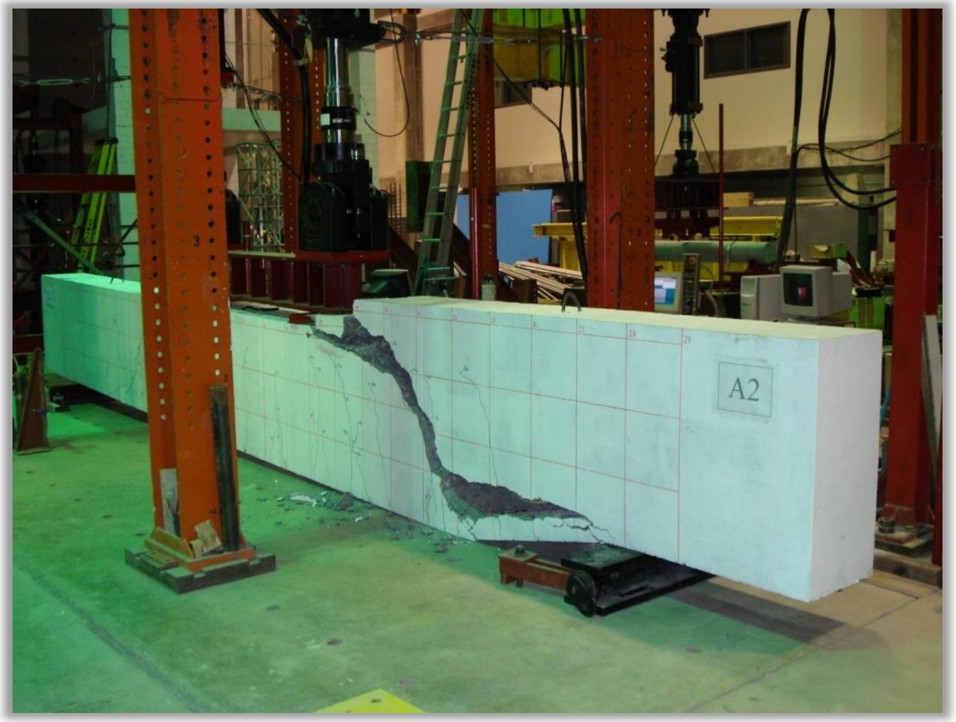


Size Effect

Session 3b: *Shear Behavior*



Beam B1-1



Beam B1-2

Diagonal Tension Failure Mode

Shear Behaviour of Concrete Bridge Girders Reinforced with FRP Stirrups (T-Section) – MTQ Research Project (2007-2009)

Shear Failure of SC-9.5-2 (CFRP @ d/2)

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Shear Behaviour of Concrete Bridge Girders Reinforced with FRP Stirrups (T-Section) – MTQ Research Project (2007-2009)

Reinforcing Cage and Concrete Casting

Shear Behaviour of Concrete Bridge Girders Reinforced with FRP Stirrups (T-Section) – MTQ Research Project (2007-2009)

Curing and transportation

Session 3b: *Shear Behavior*

Shear Behaviour of FRP RC Beams

GFRP-Cages

Session 3b: *Shear Behavior*

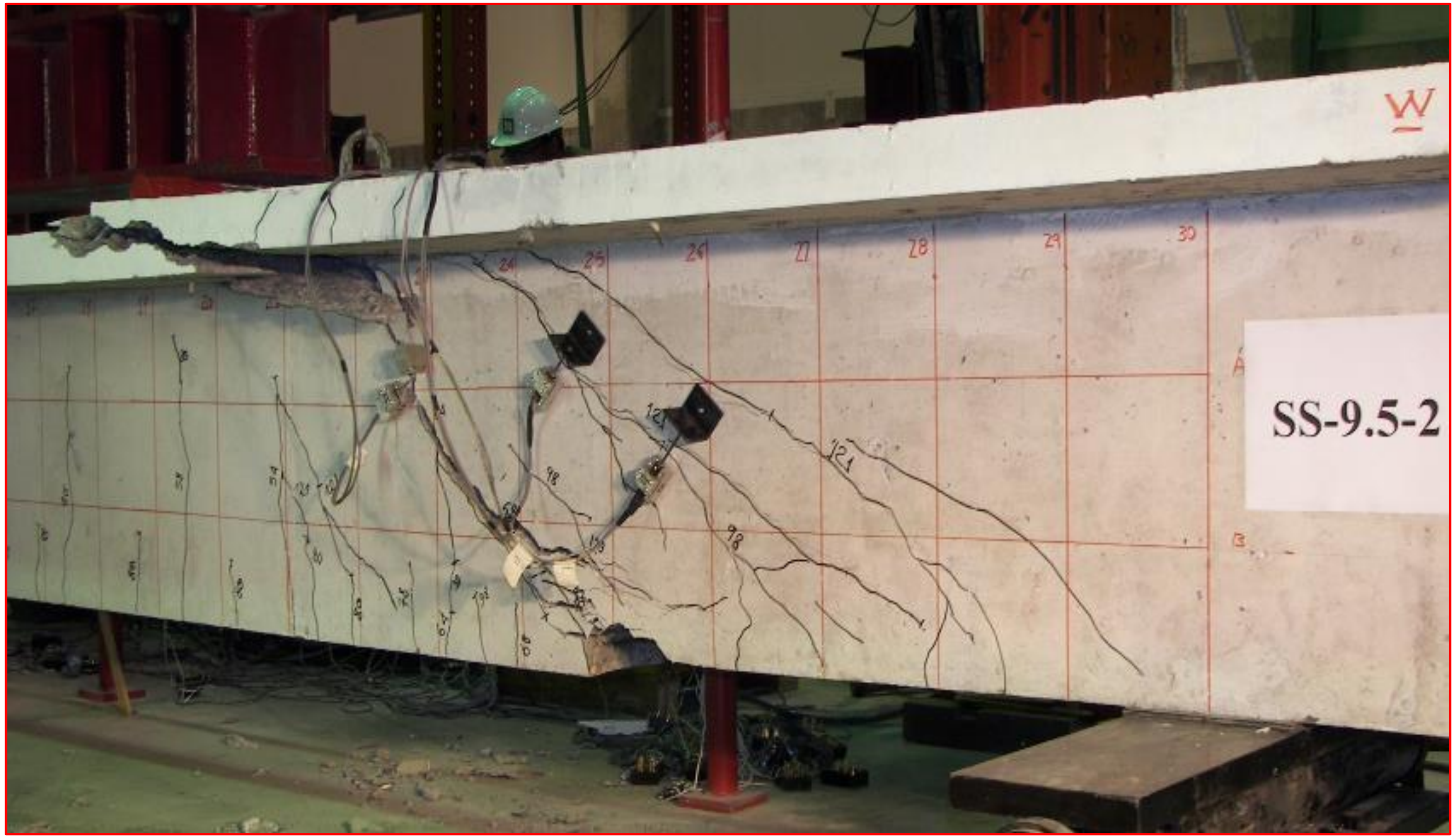
Shear Behaviour of FRP RC Beams; GFRP & CFRP Stirrups

CFRP Stirrups

Shear Behaviour of Concrete Bridge Girders Reinforced with FRP Stirrups (T-Section) – MTQ Research Project (2007-2009)

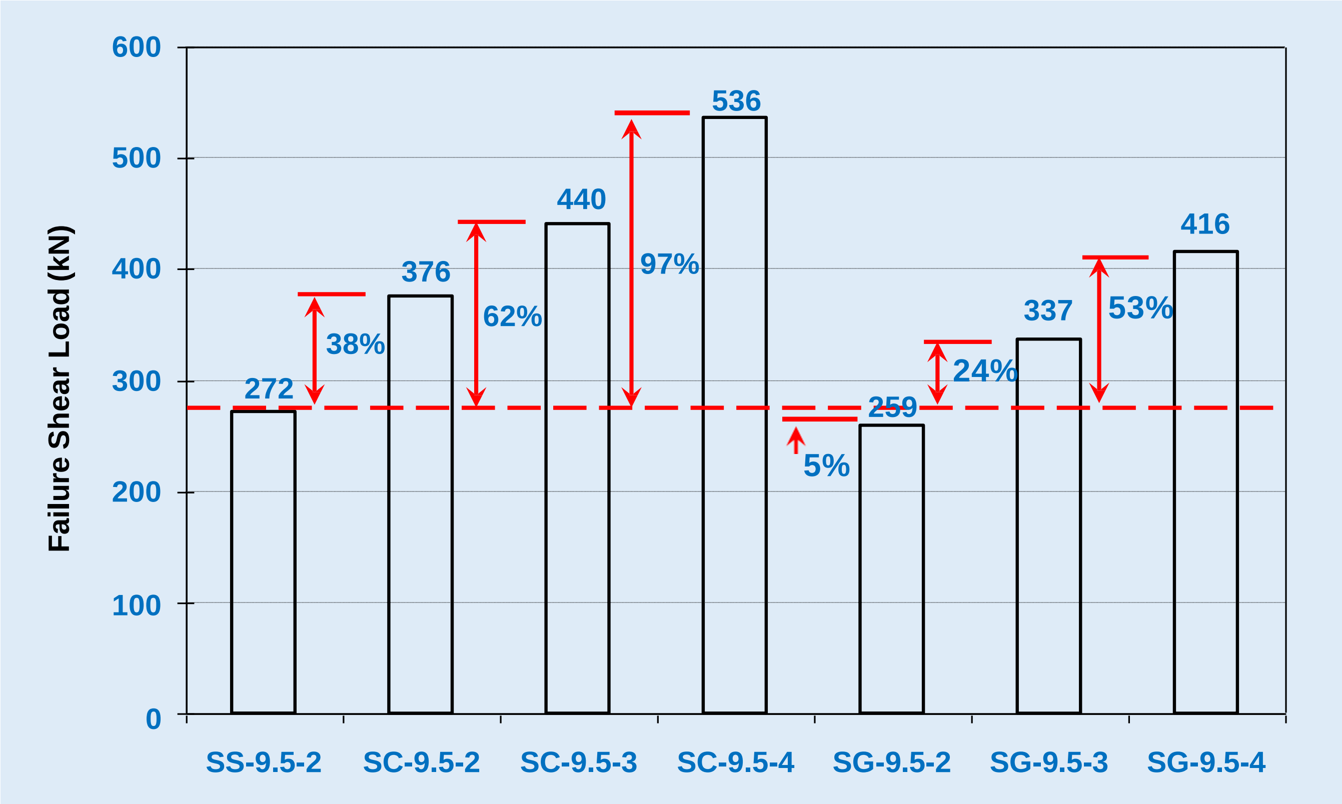
Shear Failure of SC-9.5-3 (CFRP @ d/3)

Shear Behaviour of Concrete Bridge Girders Reinforced with FRP Stirrups (T-Section) – MTQ Research Project (2007-2009)



Shear Failure of SS-9.5-2 (Steel @ d/2)

Shear Behaviour of Concrete Bridge Girders Reinforced with FRP Stirrups (T-Section) – MTQ Research Project (2007-2009)



Shear Capacity

Session 3b: *Shear Design* ***(CSA-S806)***

Shear design is similar to the simplified method of CSA A23.3-14, i.e.

$$V_r \geq V_c + V_{s,F}$$

V_c accounts for

- Shear resistance of uncracked concrete
- Aggregate interlock
- Dowel action of the longitudinal reinforcement
- Arching action

$V_{s,F}$ = Shear carried by the FRP shear reinforcement

Session 3b: *Shear Design* ***(CSA-S806)***

- For FRP Stirrups

$$V_r = V_c + V_{s,F}$$

- For Steel Stirrups

$$V_r = V_c + V_{s,F}$$

- **However, V_r shall not exceed**

$$V_{r,\max} = 0{,}22\varphi_c f_c' b_w d_v + 0{,}5V_p + \left[\frac{M_{dc}V_f}{M}\right]$$

Session 3b: *Shear Design* ***(CSA-S806)***

If the member effective depth does not exceed 300 mm and there is no axial load:

$$V_c = 0.05\lambda\varphi_c k_m k_r \left(f_c'\right)^{1/3} b_w d_v$$

where

$$k_m = \sqrt{\frac{V_f d}{M_f}} \leq 1$$

$$k_r = 1 + (E_F \rho_{Fw})^{1/3}$$

BUT

$$V_c \leq 0.22\varphi_c \sqrt{f'_c} b_w d_v$$

$$V_c \geq 0.11\varphi_c \sqrt{f'_c} b_w d_v$$

$$f_c' \leq 60 MPa$$

or if the member effective depth exceeds 300 mm and transverse shear reinforcements are equal or greater to $A_{v,min}$ (Clause 8.4.4.8)

Session 3b: *Shear Design* ***(CSA-S806)***

To account for size effect, for sections with an effective depth greater than 300mm and with less transverse reinforcement than $A_{v,min}$

$$V_c = 0.05\lambda\varphi_c k_m k_r k_s \left(f_c^{'}\right)^{1/3} b_w d_v$$

where

$$k_s = \frac{750}{450 + d} \leq 1$$

Session 3b: *Shear Design* ***(CSA-S806)***

- Shear Carried by Transverse Reinforcement

  - For Members with FRP Transverse Reinforcement

$$V_{s,F} = \frac{0.4\varphi_F A_{Fv} f_{Fu} d_v}{s}\cot\theta$$

  - For Members with Steel Transverse Reinforcement

$$V_{s,s} = \frac{\varphi_S A_v f_y d_v}{s}\cot\theta$$

f_{Fu} shall not be greater than $0.005E_F$

Session 3b: *Shear Design* ***(CSA-S806)***

- Minimum Shear Reinforcement
  - A minimum area of shear reinforcement shall be provided in all regions of flexural members where

$$V_f > 0.5V_c + \Phi_F V_p, \text{ or } T_f > 0.5T_{cr}.$$

This requirement may be waived for:
•Slabs and footings
•Concrete joist construction
•Beams with total depth not greater than 250 mm
•Beams cast integrally with slabs where overall depth is not greater than one-half the width of the web or 600 mm.

Session 3b: *Shear Design* ***(CSA-S806)***

- Minimum Shear Reinforcement
  - The minimum are of FRP shear reinforcement shall be such that

$$A_{vF} = 0.07\sqrt{f_c^{'}}\,\frac{b_w s}{0.4 f_{Fu}}$$

f_{Fu} shall not be greater than 1200MPa or 0.005E_F.

Session 3b: *Shear Design* ***(CSA-S806)***

- **Shear resistance is calculated as:**

$$V_r = V_c + V_{sf} \leq 0.25\phi_c f_c^{'} b_w d_{long}$$

Where $$V_c = 2.5\ \beta\ \phi_c\ f_{cr}\ b_v\ d_{long}$$

$$V_{sf} = \frac{\phi_{frp}\ A_{fv}\ f_{fv}\ d_{long} \cot\theta}{s}$$

$$d_{long} = 0.72h \quad or \quad 0.9d$$

Session 3b: *Shear Design* ***(CSA-S806)***

Simplified Method

For sections with at least minimum shear reinforcement

$$\theta = 42^o$$

$$\beta = 0.18$$

For sections without minimum shear reinforcement

$$\theta = 42^o$$

$$\beta = \frac{230}{1000 + d_{long}}$$

Session 3b: *Shear Design* ***(CSA-S806)***

General Method

$$\beta = \frac{0.4}{\left(1+1500\,\varepsilon_x\right)} \cdot \frac{1300}{\left(1000+S_{ze}\right)}$$

$$\theta = \left(29+7000\,\varepsilon_x\right)\left(0.88+S_{ze}/2500\right)$$

$$S_{ze} = 300mm$$

$$\varepsilon_x = \frac{\left(M_f / d_{long}\right)+V_f}{2\,E_{fl}A_{fl}}$$

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Session 3b: *Shear Design* ***(CSA-S806)***

The stress in FRP stirrup, f_{fv} , is calculated as:

$$f_{fv} = 0.004\,E_{fv} \le f_{bend}$$

$$f_{bend} = \left(0.3 + 0.05\frac{r_b}{d_b}\right) f_{fuv} \le f_{fuv}$$

Session 3b: *Shear Design* ***(CSA-S806)***

- **Minimum Shear Reinforcement**

$$A_{fv,\min} = 0.06\sqrt{f_c'}\,\frac{b_w\,s}{f_{fv}}$$

$$s \le 0.75\,d_v \quad or \quad 600mm \quad if \quad V_f < 0.1\phi_c f_c' b_w d_{long}$$

$$s \le 0.33\,d_v \quad or \quad 300mm \quad if \quad V_f > 0.1\phi_c f_c' b_w d_{long}$$

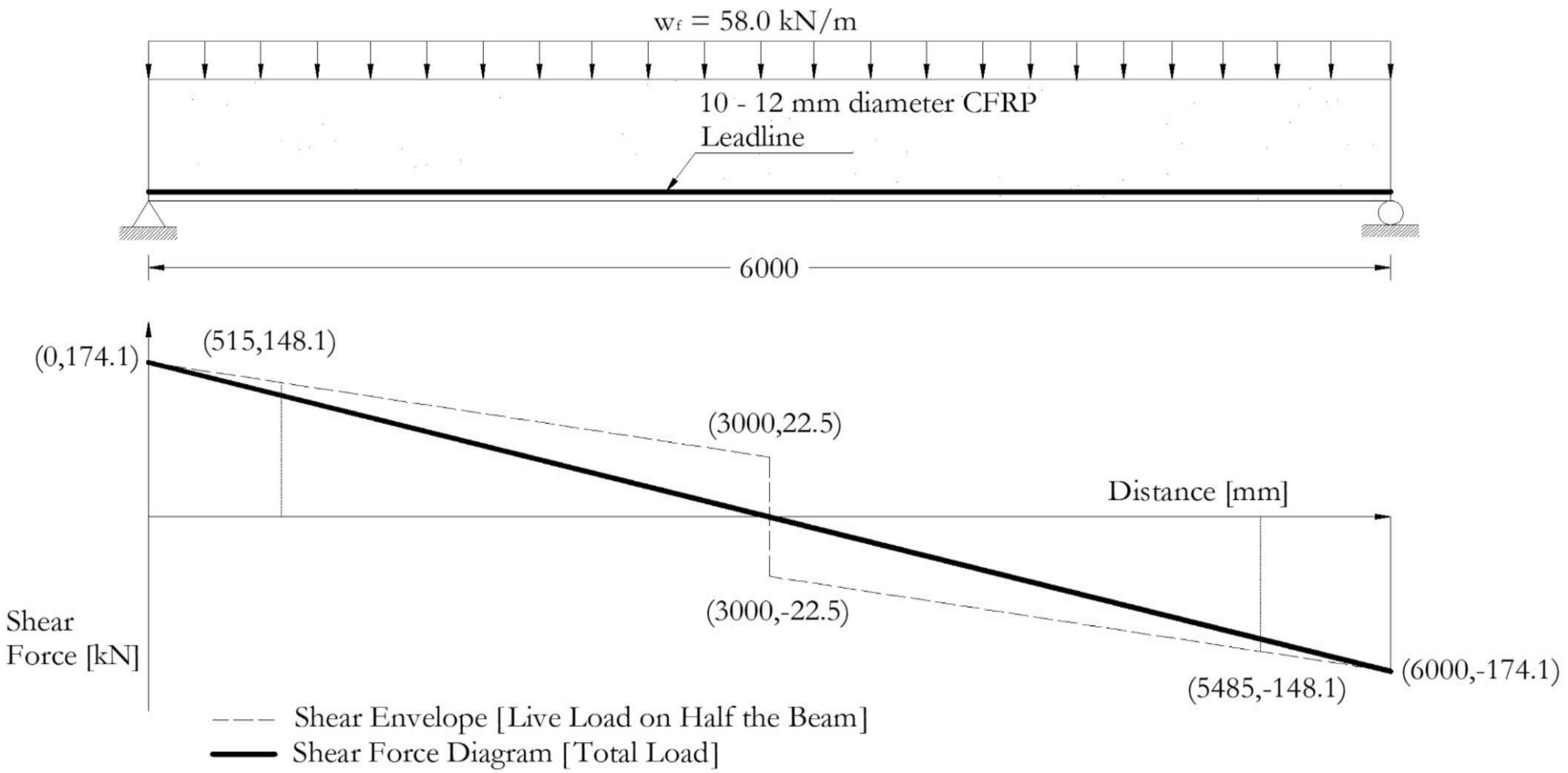
Session 3b: *Shear Design Example* ***(CSA-S806)***

A normal density concrete beam needs to carry a dead load of 17.5 N/mm and live load of 20 N/mm over a 6000 mm single span in addition to its own self-weight. Information on the beam cross-section and longitudinal reinforcement is provided below. Determine the required amount of shear reinforcement using GFRP ISOROD Stirrups.

GIVEN:

Dimensions: $b = 350$ mm $d = 515$ mm $h = 600$ mm $L = 6000$ mm
Concrete Strength: $f'_c = 40$ MPa
Flexural Reinforcement: $A_{frp} = 1131$ mm^2 [2 Layers] $E_{frp} = 147$ GPa, $d_v = 464$ mm
Shear Reinforcement: $f_{frpv} = 770$ MPa $E_{frpv} = 43.9$ GPa
Section Properties: $M_R = 418.9\text{x}10^6$ N·mm $M_{ser} = 149\text{x}10^6$ N·mm $w_{ser} = 33$ N/mm
$V_{ser} = 99.3 \text{ x } 10^3$ N [Support]

Session 3b: *Shear Design Example* ***(CSA-S806)***



Session 3b: *Shear Design Example* ***(CSA-S806)***

CAN/CSA-S6-14 Design Code

Factored Load

$$w_u = 1.2\ w_{DL} + 1.7\ w_{LL}$$

$$w_u = 1.2\ (17.5+5\ kN/m) + 1.7\ (20\ kN/m)$$

$$w_u = 61\ kN/m$$

Session 3b: *Shear Design Example* ***(CSA-S806)***

CAN/CSA-S6-14 Design Code

Shear and moment at critical section:

(at a distance d_{long} away from the support; d_{long}=463.5 mm)

d_{long}= 0.9 d =0.9x515=463.5 mm

$V_f = w_u\, L / 2 - w_u\, d_v$

V_f = 61 x 6.0 /2 – 61 x 0.4635 = 154.7 kN

M_f =61x3.0x0.4635 – 61x(0.4635)^2/2=78.3 kN.m

Session 3b: *Shear Design Example* ***(CSA-S806)***

CAN/CSA-S6-14 Design Code V_{cf}:

$$V_c = 2.5\ \beta\ \phi_c\ f_{cr}\ b_v\ d_{long}$$

$$f_{cr} = 0.4\sqrt{f_c'} = 0.4\sqrt{40} = 2.53\,MPa < 3.2\,MPa$$

$$\beta = \frac{0.4}{(1+1500\,\varepsilon_x)} \cdot \frac{1300}{(1000+S_{ze})} \qquad S_{ze} = 300mm$$

$$\varepsilon_x = \frac{\left(M_f/d_{long}\right)+V_f}{2\,E_{fl}A_{fl}} = \frac{(78.3/0.515)+154.7}{2\times1131\times147000}\times1000 = 0.001 < 0.003$$

$$\beta = \frac{0.4}{(1+1500\times0.001)} \cdot \frac{1300}{(1000+300)} = 0.267$$

Session 3b: *Shear Design Example* ***(CSA-S806)***

CAN/CSA-S6-14 Design Code

$$V_c = 2.5 \times 0.267 \times 0.75 \times 2.53 \times 350 \times 463.5 \times 10^{-3} = 205.47\ kN$$

$V_c > V_f$ **Use minimum stirrups**

$$s_{max} = \frac{A_{fv} f_{fv}}{0.06\sqrt{f'_c}\, b_w}$$

$$s_{max} = \frac{2 \times 71.26 \times 0.004 \times 43900}{0.06\sqrt{40} \times 350} = 188mm$$

Use GFRP No. 3 stirrups with s=180 mm

Session 3b: *Shear Design Example* ***(CSA-S806)***

CAN/CSA-S806-12 Code

Factored Load

$w_{sw} = 0.35 \times 0.60 \times 24 = 5$ kN/m

$w_u = 1.25\ w_{DL} + 1.5\ w_{LL}$

$w_u = 1.25\ (17.5 + 5$ kN/m$) + 1.5\ (20$ kN/m$)$

$w_u = 58$ kN/m

Session 3b: *Shear Design Example* ***(CSA-S806)***

CAN/CSA-S806-12 Code

Shear and moment at critical section:

(at a distance d_v away from the support; d_v=463.5 mm)

$$V_u = w_u\, L / 2 - w_u\, d$$
$$V_u = 58 \times 6.0 /2 - 58 \times 0.4635 = 147.12 \text{ kN}$$
$$M_u = w_u\, (L/2)\, d - w_u\, d^2/2$$
$$M_u = 58 \times 3.0 \times 0.4635 - 58 \times 0.4635^2/ 2$$
$$= 74.4 \text{ kN.m}$$

Session 3b: *Shear Design Example* ***(CSA-S806)***

CAN/CSA-S806-12 Code **V_{cf}:**

$$V_{cf} = 0.05\,\lambda\,\phi_c\,k_m\,k_r\left(f_c^{'}\right)^{1/3} b_w d_v$$

$$d_v = 0.7 \times 600 = 420mm \quad or \quad 0.9 \times 515 = 463.5mm$$

$$d_v = 463.5mm$$

$$\rho_{fw} = \frac{1131}{350 \times 515} = 0.0063$$

$$k_m = 1 + (147000 \times 0.0063)^{1/3} = 10.75$$

$$k_r = \sqrt{\frac{V_u}{M_u} d} = \sqrt{\frac{147.12 \times 0.515}{74.4}} = 1.0 \quad ok$$

$$k_a = 1.0$$

$$V_{cf} = 0.05 \times 1 \times 0.6 \times 10.75 \times 1.0 \times (40)^{1/3} \times 350 \times 463.5 \times 1.0 \times 10^{-3}$$
$$= 178.9 \quad kN$$

Session 3b: *Shear Design Example* ***(CSA-S806)***

CAN/CSA-S806-12 Code

$V_{cf} > V_f$

Use minimum shear reinforcement

$$f_{fu} \leq 0.005E_f = 0.005 \times 43900 = 219.5 < 1200\ MPa \quad ok$$

$$A_{sf} = 0.07\sqrt{f_c'}\,\frac{b_w\,s}{0.4f_{fu}}$$

GFRP No. 3 $\quad 2 \times 71.26 = 0.07\sqrt{40}\,\frac{350 \times s}{0.4 \times 219.5} \qquad s = 80\ mm$

GFRP No. 4 $\quad 2 \times 126.68 = 0.07\sqrt{40}\,\frac{350 \times s}{0.4 \times 219.5} \qquad s = 143\ mm$

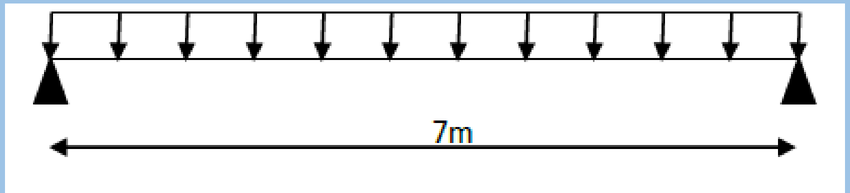
Use GFRP stirrups No.4 @140mm

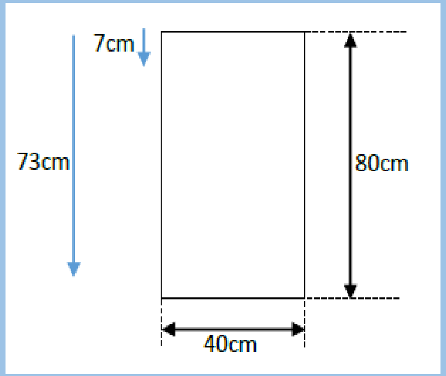
Additional Shear Design of Beam Reinforced with GFRP Bars According to ***CSA S806-12***

Session 3b: *Shear Design Example* ***(CSA-S806)***

Loads:

- **Dead load (D.L) = 85 kN/m**
- **Live load (L.L) = 40 kN/m**





Service limit state ($W_{s.l.s}$) = 85 + 40 = 125 kN/m

Ultimate limit state ($W_{u.l.s}$) = 1.25 * 85 + 1.5 * 40 = 166.25 kN/m

	S.L.S	U.L.S
V = W L / 2 (kN)	*437.50*	*581.88*
M = W L^2 / 8 (kN.m)	*765.63*	*1018.28*

Session 3b: *Shear Design Example* ***(CSA-S806)***

Mechanical Properties

- **Concrete**

  $f_c' = 30$ MPa

- **GFRP (Grade III)**

  GFRP straight bar #8 (25 mm-diameter)

  $A_f = 506.7\ mm^2$; $E_f = 66.4$ GPa; Guaranteed tensile strength (f_{fu}) = 1000 MPa.

  GFRP bent bar #3 (10 mm-diameter)

  $A_f = 71.3\ mm^2$; $E_f = 50$ GPa; Guaranteed tensile strength (f_{fu}) = 460 MPa.

Session 3b: *Shear Design Example* ***(CSA-S806)***

Notes and Assumptions

- Concrete cover = 30 mm or $2d_b$ (Clause 8.2.3).
- Assume exterior exposure of the beam for crack control.
- Minimum clear spacing between longitudinal bars = 20 mm (for vertical and horizontal spacing).
- Concrete resistance factor (φ_c) = 0.65 (Clause 6.5.3.2).
- GFRP resistance factor (φ_{FRP}) = 0.75 (Clause 7.1.6.3).
- Bond dependent coefficient (k_b) = 0.8 (sand-coated bars)

Session 3b: *Shear Design Example* ***(CSA-S806)***

Design Steps

Design for shear force

- ❖ **Calculate concrete contribution.**
- ❖ **Calculate GFRP stirrups contribution**

Session 3b: *Shear Design Example* ***(CSA-S806)***

Shear Design

Shear force at distance d_v Clause 8.4.4.2

d_v = effective shear depth, taken as the greater of 0.9d or 0.72h

d_v = Max (0.9*716.6 or 0.72*800) = 644.97 mm

$V_{design\ U.L.S}$ = 581.875 – 166.25 * 0.645 = 474.65 kN

$V_r = V_c + V_{sF}$ Equation 8.14

$V_{r,max} = 0.22\varphi_c f'_c b_w d_v$ Equation 8.16

Session 3b: *Shear Design Example* ***(CSA-S806)***

Shear Design

- Concrete contribution *(Clause 8.4.4.2)*

$$0.11\varphi_c\sqrt{f_c'}b_w d_v \le V_c = 0.05\lambda\varphi_c k_m k_r \left(f'_c\right)^{1/3} b_w d_v k_s$$

$$\le 0.22\varphi_c\sqrt{f_c'}b_w d_v$$

$$M_f = 581.875 * 0.645 - 166.25 * 0.645^2/2 = 340.72\ kN.m$$

$$k_m = \sqrt{\frac{V_f d}{M_f}} \le 1.0 \rightarrow k_m = \sqrt{\frac{474.65x716.6}{340.72x1000}} = 0.999$$

$$k_r = 1 + \left(E_f \rho_{Fw}\right)^{1/3} \rightarrow k_r = 1 + (66400 * 0.0283)^{1/3} = 13.34$$

$$k_a = \frac{2.5}{\frac{M_f}{V_f d}} \rightarrow k_a = 1 + \frac{2.5}{\frac{340.72 * 1000}{474.65x716.6}} = 2.496$$

Session 3b: *Shear Design Example* ***(CSA-S806)***

Shear Design

- Concrete contribution *(Clause 8.4.4.2)*

$$k_s = \frac{750}{450+d} \rightarrow k_s = \frac{750}{450+716.6} = 0.643$$

$$0.11\varphi_c\sqrt{f_c'}b_w d_v = 0.11 * 0.65 * \sqrt{30} * 400 * 644.97 = 101.03\,kN$$

$$V_c = 0.05 * 0.65 * 0.999 * 13.34 * 30^{1/3} * 0.643 * 400 * 644.97 * 2.496 = 557.1kN$$

$$0.22\varphi_c\sqrt{f_c'}b_w d_v = 0.22 * 0.65\sqrt{30} * 400 * 644.97 = 202.07\,kN$$

$$\boldsymbol{V_c = 202.07\,kN}$$

Session 3b: *Shear Design Example* ***(CSA-S806)***

Shear Design

- **GFRP stirrups contribution**

$$V_{SF} = \frac{\varphi_F A_{Fv} f_{Fu} d_v}{s} \cot\theta$$ *Equation 8-22*

$$\theta = 30^o + 7000\varepsilon_l$$ *Equation 8-24*

$$\varepsilon_l = \frac{\frac{M_f}{d_v} + V_f}{2(E_f A_f)}$$ *Equation 8-25*

$$\varepsilon_l = \frac{\frac{340.72 * 106}{644.97} + 474.65 * 103}{2(66400 * 8107.2)} = 0.00093$$

Session 3b: *Shear Design Example* ***(CSA-S806)***

Shear Design

- **GFRP stirrups contribution**

$$\theta = 30^o + 7000 * 0.00093 = 36.52\,°$$

Assuming stirrups #3 each 150 mm c.c

$$V_{SF} = \frac{0.75 * (2 * 71.3) * 460 * 644.97}{150} \cot 36.52\,° = \mathbf{285.66\ kN}$$

$$V_r = V_c + V_{SF} = 202.07 + 285.66 = 487.73\ kN > V_f$$

Session 1: Introduction

End of Session

Questions

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